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Advances on Biological Rhythmic Pattern Generation: Experiments, Algorithms and Applications

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As an engine of almost all life phenomena, the motor information generated by the nervous system plays a critical role in the activities of all animals. A fundamental question as to how biological rhythmic patterns are generated has puzzled many generations of scientists since Aristotle's era. With the development of natural, medical sciences and computing techniques, we are now able to speculate and demonstrate many biological motion phenomena in terms of their originating cortical areas, causes and effects, and even some of the underlying neuronal mechanisms.

Basically, all animals, either vertebrate or invertebrate, have two types of movements, i.e., voluntary or involuntary. In primates, voluntary movements are driven by the animal's will, and usually involve the high level central nervous system including the primary motor cortex, premotor cortex, supplementary motor area, and basal ganglia. These cortical areas are interconnected directly or indirectly and possibly some of these areas share the overlapped functions such that the intact areas of cortex take over the function of damaged or disconnected areas. However, aging, degeneration or traumatic injury of some cortical motor areas can have serious consequences, such as paralysis. For instance, the dysfunction of basal ganglia is commonly understood to cause Parkinson's disease. On the other hand, involuntary movements are relatively low level motion, normally involving low level nervous systems like the spinal cord or cerebellum. These movements come with the species and habits, and are usually automatic. For instance, a newly born baby is able to breathe and suck for eating. These innate movements, along with some postnatal acquired actions, like gait patterns, are speculated as outcomes of a type of mechanism, known as CPG — Central Pattern Generator. Studies of this mechanism have aroused remarkable interest in the scientific community, as its concept is biologically plausible and potentially useful in applications in other domains, though anatomically not yet clearly identified.

One can identify two main research threads in the exploration of mechanisms of pattern generation: one is on biological experiments; and the other is on mathematical and/or computational models, and associated applications. In the former approach, motion related areas in the brain are investigated, in vivo or in vitro, in order to build up an overall map of the architecture and functionality of animal motion. These studies sometimes include not only the brain areas themselves, but also their interactions with the world, via a range of sensors in a closed-loop. Some non-invasive techniques, like the electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI), are also commonly used in this thread. In recent decades, the modelling and application thread, based on biological experiments, becomes active thanks to modern technology. Two sub-threads, one regarding theoretic and computational modelling, and the other regarding neuromorphic implementation of speculated or biologically discovered mechanisms, co-exist and both develop rapidly. The outcomes of the second sub-thread start to contribute to medical practices, such as rehabilitation of disable persons.

This special issue aims to summarise recent developments and thus tries to pave a way towards understanding the underlying mechanisms of biological rhythmic pattern generation. The 16 contributed works bring us some insightful thoughts in a broad area of motion formation from various points of view, e.g., brain data acquisition and processing, computational neuroscience, mathematical models and simulation, and neuromorphic implementation. These contributions will be briefly introduced as follows, in an order of their presentation.

Heitmann *et al.* presents a mathematically stringent model demonstrating how cortical oscillations can be translated into non-rhythmic movements. A large amount of simulated works, which incorporate computational approaches and neurophysiological data, are conducted to illustrate the coherence between the simulated cortex and muscle actions in details.

It is followed by two papers of a same group about EEG data acquisition and processing. The first of these two proposes a novel approach, based on graph theory, to detect and quantify events across the scalp in response to specific cognitive tasks in the process of analysis of functional brain networks derived from multi-channel EEG data. The second suggests a new thresholding algorithm to detect subtle cognitive load induced changes in functional brain networks as shown in EEG. Both empirical analyses and statistical evaluation of the identified outcomes have been used to validate the efficiency of the thresholding algorithm.

In the past decades, legged locomotion has been extensively modelled and novel control approaches proposed, largely by using coupled neuron oscillators. Following this tradition, this issue collects four pieces of work adopting Integrate-and-Fire, Hodgkin-Huxley-like, Wilson-Cowan and Van der Pol model neurons for building CPG controllers. Rostro-Gonzalez *et al.* uses a reverse engineering process for obtaining Integrate-and-Fire CPG model parameters, mainly the synaptic weights, for producing three gait patterns. They also implemented their model in field programmable gate arrays (FPGAs) by using digital circuit technology. Elices *et al.* introduces a closed-loop minimal CPG model built by a pair of closed-loop, inhibitorily coupled neurons of the Hodgkin-Huxley type. The proposed model is able to produce different spiking-bursting activities corresponding to different choices of model parameters. In Barron-Zambrano *et al.*'s work, Van der Pol oscillators are used to build a CPG, which is a hybrid controller using a finite state machine and fuzzy logic to integrate visual information for modulating locomotion patterns. Their results show that it is possible to generate complex locomotion behavior from the modulation of simple periodic signals generated by Van der Pol CPG structures incorporating visual information in the locomotion process. Another hybrid locomotion controller, presented by Ferreira *et al.*, uses a combination of a feedforward CPG module and a feedback reflex module to produce regular stepping patterns. Zheng *et al.*'s CPG model is constructed by using the classical Wilson-Cowan neural oscillators in order to decide locomotion conditions. Inspired by a hybrid bio-machine locomotion system in the Ratbot, the model is shown to be able to predict the walking direction and relative velocity in complex maze learning tasks.

In addition to bio-inspired CPG models, several algorithm-driven CPG models can prove usefulness in wide applications. Staffa *et al.* proposes a general framework for the development of a behavior-based robot that relies on the use of the CPG mechanism modelled as an adaptive innate releasing mechanism. The CPG is deployed to balance sensory and cognitive resources, and to coordinate multiple activities in which the robot is engaged. Another CPG model, based on the scheduling by multiple edge reversal algorithm, is presented by Carvalho *et al.* in order to generate gait pattern

transition and to improve walking stability of a legged robot by means of inserting supporting phases between swing and stance leg phases.

Interestingly, CPGs can also be considered in the control of other forms of activities, not only locomotion pattern formation. Van der Velde *et al.* builds a CPG model to manipulate information retrieval for signal processing in the language cognitive process.

Another hotspot in studying the role of the central pattern generation mechanism is to look at its interaction with the associated mechanic body and environment. Huang *et al.*'s work uses kinematics analysis and simulation to demonstrate that a CPG system is more flexible, adaptive and robust in terms of rejecting disturbance, compared with a system without CPG mechanisms.

Finally, some more works are included to expand our view about biological patterns and their applications. Lu *et al.*'s paper shows an adaptive guidance system for the assistive robotic walker, which is potentially useful in assisting elderly in walking for rehabilitation purpose. Gandhi *et al.*'s work, on the other hand, use quantum neural network to filter EEG signals, which is potentially beneficial to build assistive robots. Collective behaviors of multi-robots have to be controlled by some dedicated algorithms. Li *et al.* tackles this issue through reinforcement learning. Their work is designed to control multi-robots coordination and trajectory in pursuit of a common object, which is verified through simulation studies. The last, but not the least, piece of work presented by Wang *et al.* details an interesting and mathematically strict method for saliency detection which is favorably compared with a range of existing saliency detection algorithms. It is interesting to point out that the Dijkstra's algorithm used in their model is a close relative to the scheduling by multiple edge reversal algorithm, a base of a CPG model also presented in this issue. This can reveal an interesting and essential point that some models, though looking not correlated, could fundamentally share some common points.

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